

INTRACLUSTER RED GIANT STARS IN THE VIRGO CLUSTER¹

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ABSTRACT

We have used the WFPC2 camera of the *Hubble Space Telescope* to obtain deep F814W images of a blank field in the Virgo Cluster located 41' northwest of M87. We perform star counts in that field, and in another Virgo field observed by Ferguson, Tanvir, & von Hippel (1998), and show that, when compared to the Hubble Deep Field North and South, the Virgo Cluster contains an excess of objects with magnitudes $I \gtrsim 27$. We attribute this excess to a population of intracluster red-giant branch (IC-RGB) stars. By modeling the luminosity function of these stars, we show that the tip of the Virgo RGB is at $I_{TRGB} \sim 27.31^{+0.27}_{-0.17}$ and that the cluster contains a small, but significant, excess of stars that are up to ~ 1 mag brighter than this tip. If this luminous component is due entirely to stars on the asymptotic giant branch (AGB), it implies an age for the population of > 2 Gyr; if foreground RGB stars contribute to the luminous tail, then the derived age for the stars is older still. The luminosity function also suggests that most of the intracluster stars are moderately metal-rich ($-0.8 \lesssim [\text{Fe}/\text{H}] \lesssim -0.2$), a result consistent with that expected from stars that have been tidally stripped from intermediate luminosity galaxies. Additionally, a comparison with the planetary nebulae in our field also supports this view, although the existence of a more metal-poor population (from stripped dwarfs) cannot be ruled out. Our derived average surface brightness, $\mu_I = 27.9^{+0.3}_{-0.5}$ mag arcsec⁻² for Virgo's diffuse component suggests that intracluster stars contribute 10% to 20% of the cluster's total I -band luminosity.

Subject headings: galaxies : clusters : individual (Virgo) — galaxies: interactions — galaxies: evolution — galaxies: formation

1. INTRODUCTION

Intracluster stars (stars associated with galaxy cluster *potentials*, rather than with any particular galaxy) provide an important clue towards the understanding of the formation and evolution of galaxies and galaxy clusters. N-body simulations show that this diffuse component can be produced by a number of processes. For instance, tidal interactions between merging galaxies (Miller 1983; Weil, Bland-Hawthorn, & Malin 1997; Dubinski 1999), between a galaxy and the cluster potential (Merritt 1984; Dubinski 1999), and between galaxies during high speed encounters (*i.e.*, 'galaxy harassment'; Moore et al. 1996, 1998) can all liberate stars (and globular clusters, e.g., West et al. 1995) into intracluster space. Alternatively, a significant number of intracluster stars may be created early on during a cluster's initial collapse (Merritt 1984). By observing these stars and determining their photometric and kinematic properties, we can therefore learn about the workings of tidal-stripping, the distribution of dark matter around galaxies, and the initial conditions of cluster formation.

Unfortunately, observational studies of intracluster light are very difficult due to its very low surface brightnesses (typically $\mu_B \gtrsim 27$ mag arcsec⁻², or less than 1% of the background sky). Consequently, though the first detection of diffuse intracluster light was made a full half-century ago (Zwicky 1951) and there have been numerous studies thereafter (e.g., Oemler 1973; Matilla 1977; Melnick, White, & Hoessel 1977; Thuan & Kormendy 1977; Uson, Boughn, & Kuhn

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1991; Vílchez-Gómez, Pelló, & Sanahuja 1994; Bernstein et al. 1995; Gonzalez et al. 2000), there is little agreement about the most basic data. For example, even in the well-observed Coma Cluster, measurements of the fraction of intracluster light range from less than 25% (Melnick, White, & Hoessel 1977) to $\sim 50\%$ (Bernstein et al. 1995) of the total cluster luminosity.

An obvious complement to measurements of the diffuse light in clusters is the direct detection and measurement of individual intracluster stars. Although this is only possible in nearby clusters (e.g., Virgo, Fornax, Centaurus), investigations of individual stars have the advantage of removing many sources of error that typically complicate surface brightness measurements (*i.e.*, contamination by low-surface brightness dwarf galaxies, scattered light from foreground stars, flat-fielding errors, etc.). Moreover, by studying individual stars, one has the hope of determining the underlying population’s age, metallicity, and dynamical properties.

Because of their probative value, searches for intracluster stars have become common in recent years. In particular, a number of wide-field on-band/off-band [O III] $\lambda 5007$ imaging surveys for intracluster planetary nebulae (IPN) have been conducted in fields of the Virgo and Fornax Clusters (Theuns & Warren 1997; Méndez et al. 1997; Feldmeier et al. 1998; Feldmeier 2000). These studies have confirmed the existence of large numbers of intracluster stars, and have produced evidence to suggest that many of these stars are of moderate age and metallicity.

Although IPN are a powerful probe of intracluster starlight, they do have some limitations. Spectroscopy of Virgo IPN candidates by Kudritzki et al. (2000) and Freeman et al. (2000), as well as a blank-field imaging survey by Ciardullo et al. (2002) have shown that not all objects detected through narrow-band $\lambda 5007$ filters are planetary nebulae – about 20% of the detections in Virgo appear to be Ly α galaxies at $z = 3.13$. This source of contamination produces an ambiguity in the IPN analysis, which can only be broken via time-consuming spectroscopy. In addition, in order to determine the total amount of intracluster light from IPN observations, one needs to know the production rate of bright planetaries normalized to the bolometric luminosity of the stellar population. Observations demonstrate that this quantity varies by almost an order of magnitude depending on the stellar population (Peimbert 1990; Ciardullo 1995); this creates a fundamental problem of the interpretation the IPN observations. Finally, planetary nebulae are relatively rare objects: typically it takes $\sim 5 \times 10^8 L_{\odot}$ of stars to produce ~ 1 [O III] bright planetary.

An alternative approach to studying intracluster starlight is to search for the constituent red giant (RGB) and asymptotic giant branch (AGB) stars of the stellar population. RGB stars are much more numerous than planetary nebulae, and therefore surveys for their presence do not require wide-field telescopes. Moreover, translating the number counts of red giants to total population luminosity is much more straightforward: there is no ambiguity as with PN production. Finally, because the absolute magnitude of the red giant branch tip is a function of metallicity (for relatively high metallicity populations), the luminosity function of RGB and AGB stars allows us to constrain both the metallicity and age of the stellar population.

Ferguson, Tanvir, & von Hippel (1998) (hereafter FTV) were the first to detect individual RGB stars in intracluster space. By using the WFPC2 camera of the *Hubble Space Telescope* to take deep F814W (*I*-band) images of a “blank” field located $45'$ E of the central Virgo cluster galaxy M87, Ferguson et al. were able to detect the presence of intracluster red giants through the statistical excess of point sources over that seen in the Hubble Deep Field North. From their data, Ferguson et al. concluded that intracluster stars make up $\sim 10\%$ of the total stellar mass of the system.

Unfortunately, the Ferguson et al. analysis was necessarily limited. Because their survey area consisted of only one WFPC2 field, Ferguson et al. found only a small number of stars, and thus could not place significant constraints on the age or metallicity of the intracluster population. Moreover, with only the one field, Ferguson et al. could not address the question of the overall distribution of these stars. Recent discoveries of low-surface brightness arcs in other nearby clusters (Gregg & West 1998; Trentham & Mobasher 1998; Calcáneo-Roldán et al. 2000) and large field-to-field variations in the number density of Virgo IPN (Feldmeier et al. 1998) have demonstrated that intracluster stars are not distributed uniformly. Consequently, to constrain the underlying population of these stars and learn about their large-scale distribution, additional fields must be studied.

Here we present the results of a second study of Virgo intracluster RGB stars. We begin by describing our deep *HST* observations of a Virgo blank field located between M87 and M86, near the center of the cluster’s “sub-clump A” (Binggeli, Tammann, & Sandage 1987). We detail our reduction techniques, our photometric procedures, and the artificial star simulations needed to measure the errors and incompleteness of our measurements. In section 3, we combine our data with those of the FTV survey, and compare the raw Virgo Cluster stellar luminosity function (LF) with that of the North and South Hubble Deep Fields. We show that Virgo possesses a significant excess of point sources that is due to the cluster’s population of RGB and (possibly) AGB stars. In section 4, we model the point-source luminosity function, and place constraints on the cluster’s distance, and on the age and metallicity of its intracluster population(s). Finally, we discuss these results and compare them with other measures of intracluster stars.

2. OBSERVATIONS

On 5 and 6 May 2000, we conducted a search for intracluster stars by imaging a Virgo Cluster “blank field” through the F814W filter of the WFPC2 camera of the *Hubble Space Telescope*. The field, located at $\alpha_{2000} = 12^h 28^m 16^s$, $\delta_{2000} = +12^\circ 41' 16''$, lies about $41'$ NW of M87, near the center of Virgo’s subclump ‘A’ (Binggeli, Tammann, & Sandage 1987). As Figure 1 illustrates, the field is positioned far away from the bright galaxies of the cluster, and within a region surveyed for planetary nebulae by Feldmeier (2000).

The total integration time for our survey was 33800 s; these data were broken up into 13 2600 s exposures, which

were dithered to facilitate the removal of bad pixels and “fill out” the image point-spread-function (PSF). To supplement these data, we also re-reduced and analyzed the images taken by FTV in their blank field survey of Virgo. These images are very similar to ours: they consist of 13 dithered WFPC2 F814W images (10 exposures of 2600 s plus 3 exposures of 2500 s) centered on a location 45' E of M87. Finally, to serve as a control, we used data from two other locations well away from any galaxy or cluster: the Hubble Deep Field North (HDF-N; Williams et al. 1996) and South (HDF-S; Williams et al. 2000). For both HDF fields, we extracted a subset of images which, when combined, created a summed image with noise characteristics similar to that of our Virgo Field. For HDF-N, our control image was made from 13 frames (11×2600 s + 2×2700 s) totaling 34000 s; for the HDF-S, our reference image was formed from using 14 frames (8×2400 s, 3×2300 s, and single images of 2500s, 2700s and 2800s) with a total exposure time of 34100 s. For this investigation, we only considered the three WF fields of the instrument; because of its small field-of-view, the PC chip did not contain enough stars to warrant analysis.

2.1. Data Reduction

We reduced all four fields in exactly the same manner. First, we corrected our images for the small variation in pixel area (see Holtzman et al. 1995; Stetson et al. 1998) across the WF field-of-view using a pixel-area mask provided to us by Peter Stetson. We then re-registered and averaged the images using the tasks within IRAF. This resulted in a single deep I image for each chip, with virtually all the cosmic rays removed. To keep the noise characteristics of the chips relatively uniform, we then excluded those regions of each field that were not contained on most of the component images. Although this is a minor point for the two Virgo fields and HDF-N, the relative shifts (and rotations) of some of the images that went into building the HDF-S field were rather large. As a result, the useable area for this field was only 3.85 arcmin², compared to 4.69 arcmin² for HDF-N and 4.73 arcmin² for the two Virgo fields.

Once the images were combined, we equalized the photon noise for each field. Because the Virgo Cluster is located within $\sim 15^\circ$ of the ecliptic plane, the background zodiacal light in this area of the sky is slightly larger than that present in the Hubble Deep Fields. This results in a slightly noisier background on these frames. To compensate for this effect and make the comparison between fields as fair as possible, we therefore added an additional (Gaussian) component of noise ($\sigma = 0.4$ ADU) to the HDF frames. When this was done, the noise in our control fields was virtually identical to that of the cluster fields.

Photometry was carried out on each of the combined I images using the DAOPHOT II + ALLSTAR packages (Stetson 1987; Stetson, Davis, & Crabtree 1990; Stetson 1992), with a 3.5σ detection threshold. Since both the cluster and HDF fields are sparsely populated, only one DAOPHOT pass was required; secondary runs yielded few new detections. For the photometric measurements, we chose to use the I -band WF PSFs that were exhaustively derived for the *HST* Distance Scale Key Project (e.g., Hill et al. 1998; Mould et al. 2000); these data were kindly provided to us by Peter Stetson. Creation of our own PSF was problematic, due to the lack of bright, unsaturated stars in our fields. Moreover, in the few cases where suitable PSF stars were available, our derived PSF was not significantly different from that found by the Key Project.

A major concern for any deep survey which uses a single filter is the possibility of spurious identifications at the frame limit. In particular, with the relatively low detection threshold used here, it is common for positive noise excursions to be flagged as objects. To measure this effect, we applied our DAOPHOT II 3.5σ detection algorithm to the *inverse* of each image, and derived (in essence) the luminosity function of noise peaks. The result from this experiment (adding data from all 4 fields) is shown in Figure 2. Note that virtually all the detected noise spikes are fainter than the limiting magnitude (I_{lim}) of the survey (see below for the definition of I_{lim}). Although some spurious detections *brighter* than I_{lim} do exist, these objects contribute less than 1% of the total number of counts between $I = 26.6$ and 27.4. Since this is significantly smaller than the \sqrt{N} statistics that dominate our analysis, we are confident that false detections are not an important problem in our analysis.

The next step in our reduction was to remove non-stellar sources from our object lists. To do this, we used the DAOPHOT χ parameter (Stetson 1987) and r_{-2} image moment (Kron 1980); both are effective point-source image discriminators (e.g., Stetson 1987; Harris et al. 1991; McLaughlin et al. 1995). First, we determined the critical values of χ and r_{-2} from both a visual inspection of the CCD frames, and from the results of artificial star experiments (see below). Any object whose image parameters exceeded either critical value was classified as non-stellar and excluded from the analysis. To maintain consistency, the same values of χ_{crit} (1.5) and $r_{-2,crit}$ (1.16) were used on each frame, and in our artificial star simulations. From the experiments, it is clear that at magnitudes brighter than $I = 27$, our star/galaxy discrimination algorithm works well; at these magnitudes, most galaxies are successfully rejected, and very few stars are flagged as non-stellar. At fainter levels, however, the discrimination technique break down and few objects are rejected by the procedure.

2.2. Calibration

All four fields were calibrated using the prescription given in Holtzman et al. (1995). We first converted the ALLSTAR PSF-based magnitudes to 0.5 arcsec aperture magnitudes using measurements of 1 to 6 bright field stars on each WF chip; the rms scatter in this procedure was typically 0.02-0.04 mag. These aperture magnitudes were then changed to standard I magnitudes via the transformation

$$I = F814W - 0.063(V - I) + 0.025(V - I)^2 + z_I \quad (1)$$

(Holtzman et al. 1995). The zero points used were those derived by Hill et al. (1998); these are for a gain of 7 and include the ~ 0.05 mag correction required for long exposures. At this time, an additional 0.016 mag offset was also added in, to correct for differences in normalization between the Stetson pixel-area mask and the Holtzman calibration (cf. Stetson et al. 1998). Finally, as we have no color information, we assumed $(V - I) = 2$ for all objects. This value adequately represents the color of both our target RGB stars and a substantial fraction of the background galaxies. Note that the error introduced by our assumption of color (~ 0.03 mag) is small, compared to the ~ 0.2 mag photometric errors expected for RGB stars in Virgo.

2.3. Artificial Star Experiments

Because the RGB stars of Virgo are expected to be at or near our detection limit ($I \sim 27$) it is extremely important to have a complete understanding of the data's photometric errors and our observational incompleteness. To measure these quantities, we took advantage of our knowledge of the WFPC2 PSF and performed a series of artificial stars experiments. For each chip of each field, we added a total of 10000 artificial stars (in 100 simulations, with 100 stars per simulation), and re-reduced the frames in precisely the same manner as described above – a single pass of DAOPHOT II/ALLSTAR, followed by the removal of non-stellar images using our image-classification algorithm. By limiting the number of artificial stars added in each run to less than 10% of the observed objects, we ensured that our simulations did not significantly change the object density (and therefore the image crowding) of the fields. Similarly, by giving our artificial star luminosity function a positive slope ($dN/dI = 0.7$ to roughly mimic the expected behavior of stellar objects in the fields) we improved our statistics at the faintest magnitudes, where most of the real objects lie.

Figure 3 displays the results from one of our simulations: that for the Virgo A field. The upper panel of the plot displays $f(I)$, photometric completeness function, which we define as the number of artificial stars of magnitude I divided by the number of those stars recovered. Note that, due to photometric errors, the measured magnitudes of the artificial stars will not necessarily be those that were originally simulated. Specifically, for an ensemble of stars with input magnitude I_{in} , the measured magnitudes will be distributed with a dispersion $\sigma(I)$ about a measured magnitude, I_{out} , which is offset from I_{in} by an amount $\Delta I = I_{out} - I_{in}$. The center and bottom panels of Figure 3 display these two quantities.

The trends displayed in Figure 3 are representative of all our simulations. For bright objects, $f(I)$ is independent of magnitude ($f(I) \approx 1$), and the measured magnitudes are very nearly equal to the input magnitudes. However, as the stars become fainter, the photometric uncertainties become larger, and incompleteness becomes important. Moreover, for the very faintest objects, the measured magnitudes become systematically brighter than the true magnitudes. This is due to a simple selection effect: objects with positive noise spikes are detectable, while those with negative noise are not.

We can characterize the incompleteness function of any field via the expression

$$f(I) = \frac{1}{2} \left(1 - \frac{\beta(I - I_{lim})}{\sqrt{1 + \beta^2(I - I_{lim})^2}} \right) \quad (2)$$

(Fleming et al. 1995), where I_{lim} is the limiting magnitude of the data (defined as the 50% completeness level; Harris 1990), and β is a parameter that measures how steeply $f(I)$ declines from 1.0 to 0.0. Table 1 combines the artificial star experiments for the three WF chips and gives the most likely values of I_{lim} and β for each field. The strong similarity between the results for the Virgo fields and those for the control fields demonstrates that our efforts to match the noise characteristics of each field were successful.

3. LUMINOSITY FUNCTIONS

3.1. The Background LFs : HDF-N + HDF-S

Because our star/galaxy discrimination algorithm breaks down near our survey limit, the contribution of unresolved background galaxies to the faint end of our stellar luminosity function is significant. Consequently, before analyzing the cluster luminosity functions, we must first examine the unresolved object counts of our two control fields.

The top two panels of Figure 4 display the luminosity functions for the two Hubble Deep Fields. The solid points show the LFs of point sources; the histogram gives the LFs of all objects. Even a cursory inspection of the figure reveals that our star/galaxy discriminator works well only at relatively bright ($I \lesssim 27$) magnitudes; at fainter magnitudes it becomes impossible to exclude galaxies based on their image parameters. Moreover, the data clearly show that, once the HDF-S counts are scaled to match the HDF-N survey area, the LFs of the two fields are statistically indistinguishable. We can therefore sum the LFs to produce a composite ‘background’ LF based on a total area of 8.54 arcmin². This control field LF is displayed in the bottom panel of the figure.

It is important to note that the LFs of Figure 4 have *not* been corrected for photometric completeness. Our tests on the inverse science images (see section 2.2 above) demonstrate that a non-negligible fraction of the counts fainter than I_{lim} is due to noise. Consequently, measurements of objects fainter than this limit are not reliable, and have been excluded from our analysis. (However, stars *intrinsically* fainter than I_{lim} can be measured to be brighter than I_{lim} ; these are accounted for in the models below.)

3.2. Virgo Cluster Fields

Figure 5 displays the LFs for our Virgo A field and for the FTV Virgo field. Again, the solid points show the LFs for the point-like sources, while the histogram illustrates the LF of all objects. Figure 6 (and Table 2) shows the stellar LFs

with the background of Figure 4 removed. The figures clearly demonstrate that both Virgo fields contain a large excess of stellar objects at magnitudes $I \gtrsim 27$, and a slight excess of objects at magnitudes $26.4 \lesssim I \lesssim 27$. These are exactly the magnitudes where we would expect to find Virgo Cluster RGB and AGB stars.

According to ‘galaxy harassment’ models (eg. Moore et al. 1999), stars that are removed from their parent galaxies via tidal encounters retain some memory of the event which ejected them (see also Johnston et al. 1999). Consequently, if most intracluster stars are formed in this manner, we might expect the distribution of intracluster stars to be clumpy, or have significant substructure. Since our Virgo A field and the FTV field are separated by more than a degree on the sky, we might therefore expect the number of intracluster stars in the two fields to be significantly different. Figure 6 shows that this is indeed the case; we detect more unresolved objects in our Virgo A field than in the FTV field. A simple count of objects brighter than $I_{lim} = 27.65$ (to $I = 26.55$) shows that the Virgo A field contains 1.48 ± 0.17 times more point sources than the FTV field, *i.e.*, 618 ± 31 stars *versus* 418 ± 28 . These raw star counts in themselves are not particularly meaningful, since they have not been corrected for incompleteness. However, the similar *shapes* of the two background-corrected LFs is important: it, along with the derived RGB tip magnitudes (see the next section) further strengthens interpretation that the detected sources are the RGB stars of Virgo.

4. MODELLING THE LFS

The luminosity functions presented above are not corrected for incompleteness, nor do they compensate for photometric uncertainties, which move objects from one magnitude bin to another. To derive the intrinsic LF of Virgo, we need to correct for these effects. The best way to do this is to create models of Virgo Cluster’s RGB + AGB population, convolve them with the photometric error and incompleteness functions of Figure 3, compare the results to the observed data, and identify the best fitting model. Such a procedure not only allows us to fit the observed data, but also enables us to derive the density of unresolved stars in Virgo’s intracluster space.

To represent Virgo’s RGB population, we used a power-law luminosity function with a slope of $d \log N/dI = 0.4$; this is based on the stellar evolutionary tracks of Girardi et al. (2000) for populations older than 4 Gyr and sub-solar metallicities. (The precise slope of the power law makes very little difference to the final result.) We truncated the bright end of the luminosity at magnitude I_{TRGB} , a free parameter that represents the tip of the red giant branch; we followed the faint end of the LF to $I_{cut} = 28.1$, where the completeness function of Figure 3 drops below $f(I) = 0.20$. (Tests show that fainter stars have little effect on the analysis.) For the AGB component, we again followed the models of Girardi et al. (2000) and adopted a flat luminosity function ($d \log N/dI = 0$) from I_{TRGB} to $I_{TAGB} < I_{TRGB}$, with a normalization such that the AGB component contributes 15% of the stars at the RGB tip. For simplicity, we assumed that all the intracluster stars of Virgo are at a single distance (*i.e.*, no depth effects are included). We will comment on the possibility of foreground RGB/AGB stars later.

Our RGB + AGB luminosity function is shown schematically in Figure 7. Under this formulation, our input LF has three free parameters: I_{TRGB} , $\Delta I_{AGB} = I_{TRGB} - I_{TAGB}$, and the overall normalization of the model. The most-likely values for these parameters are those that minimize χ^2 in the range $26.0 \leq I \leq 27.6$. Note that because the photometric errors are large and the convolution function asymmetric, the observed luminosity function is much smoother and slightly shifted towards brighter magnitudes than the input LF. (This effect is most noticeable near I_{lim} .) Note also that though our limiting magnitude is $I \sim 27.65$, stars intrinsically fainter than this contribute significantly to the observed ($I < I_{lim}$) luminosity function. This is why an understanding of the photometric properties of these extremely faint stars is crucial for the interpretation of an observed luminosity function.

Table 3 details the parameters which best fit the LFs of Figure 6; in each case, the minimized χ^2_ν values are ~ 1 , showing that our RGB+AGB model is an acceptable match to the luminosity function. The 1σ errors are derived from fits with $\chi^2_\nu = \chi^2_{\nu,min} + 1.15$ (e.g., Press et al. 1992), which is the appropriate value to use for a three-parameter fit to 17 points. As the table shows, the models for the individual fields are not particularly well constrained: there are simply not enough stars in the FTV or Virgo A fields for a precise determination of the stellar luminosity function. However, since the shapes of the two observed luminosity functions are similar, we can combine the datasets and improve our measurement of the clusters’ RGB and AGB population. When we do this, the best fit for the RGB tip in Virgo becomes $I_{TRGB} = 27.31^{+0.27}_{-0.17}$, and $\Delta I_{AGB} = 0.8^{+0.07}_{-0.2}$. This model is plotted in the bottom panel of Figure 6. The improved precision of the model allows us to place constraints on the age, metallicity, and importance of Virgo’s intracluster stars.

4.1. Surface Brightness

Our RGB and AGB detections allow us to estimate the *I*-band surface brightness of Virgo’s intracluster space. We start with only the RGB stars: if we take our best-fitting model of Virgo’s intrinsic LF, and sum up the luminosity of all the RGB stars down to $I_{cut} = 28.1$ in the 9.46 arcmin^2 area of the two survey fields, the result is an average surface brightness of $\mu_I = 30.48^{+0.07}_{-0.03} \text{ mag/arcsec}^2$ (error based on 1σ error in I_{TRGB}). Next, we add in the AGB stars. The contribution of this component is a bit more uncertain, due to the larger error bars on ΔI_{AGB} , but when included, the Virgo intracluster surface brightness due to all stars brighter than $I = 28.1$ becomes $30.28^{+0.11}_{-0.08}$ (see also Table 3).

Finally, we must include the substantial contribution of stars fainter than the cutoff of our model luminosity function. To compute this number, we used the theoretical luminosity functions of Girardi et al. (2000), which include main-sequence stars (down to $M_I \sim +10$) as well as stars on the RGB, AGB, and horizontal branch. We investigated a grid of 15 models, with ages of 4, 8, and 12 Gyr, and with metallicities of $Z = 0.0001, 0.0004, 0.001, 0.004$, and 0.008 (here, $Z_\odot = 0.019$). Our choice of models was driven by observational considerations. Populations younger than 4 Gyr were excluded, since

these produce stars that are more than a magnitude brighter than the RGB tip; such objects are not seen in our data. Similarly, based on the brightness of the RGB stars, we did not consider stars with solar or super-solar metallicities (see the discussion below).

Since we do not know *a priori* the distance of Virgo’s intracluster stars (and therefore the absolute magnitude of the RGB tip), we parameterized our luminosity corrections in terms of ΔI_{TRGB} , the difference between the cutoff of our model luminosity function ($I = 28.1$) and the tip of the giant branch. For each Girardi et al. model, we removed the AGB component and computed F , the fraction of the total light generated by RGB stars within ΔI_{TRGB} of the giant branch tip. We then used this ratio to correct our measured surface brightness for the contribution of unobserved stars ($\mu_{true} = \mu_{obs} + \Delta\mu_{ML}$, where $\Delta\mu_{ML} = 2.5\log F$ is the ‘missing light’ contribution).

Table 4 summarizes our results. The listed values of μ_{ML} (at a given ΔI_{TRGB}) are the mean values (and associated errors) derived from the 15 model luminosity functions. This missing light correction does not depend strongly on the population’s age or metallicity, provided the stars are relatively old and not \sim solar or super-solar metallicity. When we add this unseen component ($\Delta\mu_{ML} = -2.38^{+0.18}_{-0.40}$, based on our derived values for ΔI_{TRGB}) to our previous estimate of surface brightness, we get $\mu_I = 27.9^{+0.3}_{-0.5}$ mag arcsec $^{-2}$ for the I -band surface brightness of the Virgo intracluster stars. The quoted errors on this number come from the statistical errors of the RGB and AGB components and the population uncertainties given in Table 4. The rather asymmetric errors are due to the unknown distance of the cluster: the larger the distance to Virgo, the larger the correction for unresolved sources, and the brighter the derived value of μ_I . If we assume a Virgo Cluster distance of 16 Mpc (e.g., Harris et al. 1998; Ferrarese et al. 2000; Tonry et al. 2001), this surface brightness translates into an average luminosity surface density of $\sigma_{L,I} = 0.13^{+0.08}_{-0.05} L_{\odot} \text{pc}^{-2}$.

Our average value² of $\mu_I = 27.9^{+0.3}_{-0.5}$ mag arcsec $^{-2}$ for the surface brightness of Virgo’s intracluster stars is roughly three times the luminosity derived by FTV in their study. Part of this difference is due to the $\sim 50\%$ greater number of stars detected in the Virgo A field: the derived surface brightness of the Virgo A field is $\mu_I = 27.7$, while that for the FTV field is only $\mu_I = 28.1$. The remaining offset is largely due to the correction for unresolved stars. FTV assumed that the observed RGB + AGB stars produce 16% of the total intracluster light, while our analysis suggests that this percentage is $11^{+2}_{-4}\%$. While we cannot fully explain the discrepancy, it is possible that the different results arise from differences in the treatment of the cluster’s AGB stars. The Girardi et al. (2000) models demonstrate that the contribution of these stars to a population’s total luminosity is a sensitive function of metallicity. Consequently, if one relies on the models for this phase of evolution, the uncertainty in the result can be substantial. By combining the data from the two *HST* survey fields, we have been able to observationally constrain the luminosity of the AGB component, and thereby improve the correction for unresolved stars.

With the luminosity of Virgo’s intracluster stars now fixed, we can next compare this number to the amount of light contained within the cluster’s galaxies. To do this, we used the galaxy catalog of Binggeli, Sandage, & Tammann (1985) to find the total B -band magnitudes of all member galaxies brighter than the catalog’s limit of $B_T \sim 20$. (This limit is adequate for our purpose, since the contribution of fainter systems to Virgo’s total luminosity is negligible.) We then converted these B -magnitudes to I , using the observed $B - I$ colors of early-type galaxies (Goudfrooij et al. 1994) and a mean $(B - I)$ color for the late-type galaxies (de Jong & van der Kruit 1994). Finally, with the I magnitudes of all the galaxies in hand, we computed the cluster’s I -band galactic luminosity density via a series of circular apertures centered on the giant elliptical galaxy M87. (Binggeli, Tammann, & Sandage (1987) have shown that the luminosity density of Virgo actually peaks $\sim 1^\circ$ NW of M87. However, measurements of the cluster kinematics (Binggeli, Popescu, & Tammann 1993), x-ray luminosity (Böhringer et al. 1994; Schindler, Binggeli, & Böhringer 1999), and three-dimensional shape (Jacoby, Ciardullo, & Ford 1990; West & Blakeslee 2000; Ferrarese et al. 2000; Tonry et al. 2001) demonstrate that this offset is likely due to the contribution of the M84/M86 Group, which is falling into Virgo from behind.)

Figure 8 details how Virgo’s galactic luminosity density changes with distance from M87. As can be seen, the galaxy light shows the expected monotonic decline with radius; only the ‘plateau’ between 0.5 and 1.75 , which is due to the contribution of the M84/M86 group, interrupts this trend. The figure also shows our measurement of the luminosity density of intracluster stars. If we assume that the ‘plateau’ value of the galaxy luminosity density ($\sigma_{L,I} = 0.73 \pm 0.01 L_{\odot} \text{pc}^{-2}$) is representative of the central regions of the Virgo cluster, then the intracluster component contributes $15^{+7}_{-5}\%$ of the luminous matter of the cluster. This value is larger than the $\sim 10\%$ derived by FTV value: though FTV derived only $\sim 1/3$ as much intracluster light as we do here, they also considered only the early-type galaxies in their measurement of Virgo’s galactic luminosity. Consequently, our final numbers are not that different.

If we consider the rather extreme possibility that our value for Virgo’s intracluster light is constant with radius beyond $\sim 2^\circ$ from M87, then the importance of the diffuse component would increase to about $\sim 30 - 35\%$ of Virgo’s total light. However, we believe that such a large density for Virgo’s intracluster light is unlikely, since in other clusters, the intracluster component is known to decrease with radius (e.g., Thuan & Kormendy 1977; Bernstein et al. 1995).

5. NATURE OF THE IC-RGB POPULATION

5.0.1. IC stars or M87 cD Envelope?

Our observations of Virgo’s intracluster stars raise an interesting question: are the stars seen in the Virgo A and FTV fields part of M87’s cD halo? Almost certainly, this issue has more to do with terminology than with science (see

² We have used the average results from both fields for most of the remaining analyses; there is no *a priori* reason to choose which field μ_I is more ‘representative’ as they are at similar projected distances from M87.

Vílchez-Gómez 1999, and references therein). In rich clusters, the cD envelope of the central galaxy can often be traced over many hundreds of kpc (cf. Uson, Boughn, & Kuhn 1991; Scheik & Kuhn 1994); the stars in such an envelope are almost certainly not bound to any one galaxy. Moreover, direct evidence for the intracluster nature of cD envelopes comes from the observations of NGC 1399, the central galaxy of Fornax. In this system, the stellar velocity dispersion monotonically decreases with radius out to a galactocentric distance of $R \sim 5$ kpc (e.g., Saglia et al. 2000). Once past this point, however, the velocity dispersion of the envelope rapidly increases, until, by $R \sim 13$ kpc, the dispersion of the stars and globular clusters match that of the cluster’s galaxies (Arnaboldi et al. 1994; Grillmair et al. 1994; Kissler-Patig et al. 1999). The data demonstrate that the stars in this cD envelope kinematically belong to the cluster, not the central galaxy. The radial dependence of M87’s globular cluster velocity dispersion suggests that the same thing is true for Virgo (Côté et al. 2001).

If the core of Virgo is similar to that of Fornax, then our derived surface brightness for the intracluster stars of the Virgo A and the FTV fields may very well be consistent with that expected from a smooth extrapolation of M87’s luminosity profile. To test this hypothesis, we used the surface photometry measurements of de Vaucouleurs & Nieto (1978) and Schombert (1986); both authors have traced M87’s luminosity profile out to a distance of $\sim 20'$, where it falls below their detection threshold of $\mu_B \sim 29$. If we extrapolate these measurements to the positions of our Virgo fields ($41'$ NW for Virgo A, $45'$ E for the FTV field) and assume Virgo’s diffuse light has a $B-I$ color of 1.9 (Ferguson, Tanvir, & von Hippel 1998), then we derive a background I -band surface brightness of $\mu_I \sim 30.3$ and $\mu_I \sim 31$ mag arcsec $^{-2}$, respectively. These values are more than mag fainter than we observe.³ Thus, the existence of an additional luminous component to the cluster is a possibility. However, this conclusion is far from certain; had we used the surface photometry of Carter & Dixon (1978) (see also Harris, Harris, & McLaughlin 1998) instead of that of de Vaucouleurs & Nieto (1978) and Schombert (1986), we would have derived surface brightnesses ~ 2 magnitudes *brighter* than observed. Such a discrepancy is not unexpected, given the uncertainties associated with the extrapolation of these photographic surveys.

The extremely high contrast Virgo images presented by Arnaboldi et al. (1996) and Weil, Bland-Hawthorn, & Malin (1997) are equally ambiguous. Both of these images show that extremely low-surface brightness ($\mu_B = 28$ mag arcsec $^{-2}$) structures do exist around the bright galaxies (M86 and M87) of Virgo. However, our Virgo A field lies between these features, and any tidal stream that may exist in the region is well below the detection threshold of their plates. As a result, the question of whether the detected intracluster stars are part of smooth cD envelope or a component of an irregular tidal stream cannot as yet be answered.

5.0.2. The RGB Population

The absolute magnitude of the tip of the giant branch is an extremely useful probe for extragalactic astronomy. For populations with metallicities $[\text{Fe}/\text{H}] \lesssim -0.8$ and ages more than a few Gyr, the RGB tip is remarkably constant, $M_{I,TRGB} = -4.1 \pm 0.1$; this makes the feature a useful extragalactic distance indicator (e.g., Lee, Freedman, & Madore 1993; Sakai et al. 1997; Harris et al. 1998; Ferrarese et al. 2000; Bellazzini, Ferraro, & Pancino 2001). Alternatively, in more metal rich populations, the tip of the RGB is a sensitive measure of metallicity, since line-blanketing in the I -band suppresses the emergent flux. As a result, if one already knows the distance to a stellar population, then the magnitude of the RGB tip can be used to probe metallicity. We can use this property to place a constraint on the population of Virgo’s intracluster stars.

In order to do this, we first consider the galaxy VCC 1104, a nucleated dwarf elliptical (dE,N) projected onto the core of the Virgo Cluster. According to Harris et al. (1998), this galaxy has a well-populated red giant branch, whose tip lies at $I_{TRGB} = 26.87 \pm 0.06$. (We have corrected the Harris et al. value by 0.05 mag for consistency with the Hill et al. (1998) zero points adopted in this paper.) This is $0.44^{+0.27}_{-0.18}$ mag brighter than the RGB tip of Virgo’s intracluster stars. There are two possible explanations for this offset.

The first possibility is that the observed intracluster stars are at the same distance as VCC 1104, but are more metal rich. Since VCC 1104 is a dwarf galaxy ($M_V = -16.2$; Durrell 1997), we can assume that its population is dominated by old, relatively metal-poor stars ($[\text{Fe}/\text{H}] \sim -1$; Côté et al. 2000). In this case, $M_{I,TRGB}$ of the galaxy is -4.1 , and the ~ 0.4 mag offset between the two RGB tips implies $M_{I,TRGB} = -3.66^{+0.27}_{-0.18}$ for the intracluster star population. We can translate this into a metallicity in two ways. First, we can use stellar evolution models: according to VandenBerg et al. (2000) and Girardi et al. (2000), absolute TRGB magnitudes between $I \sim -3.9$ and -3.4 correspond to metallicities between $[\text{Fe}/\text{H}] \sim -0.8$ and -0.3 . Alternatively, we can use observations of Galactic globular clusters to derive an empirical TRGB metallicity calibration. The metal-rich globular NGC 6553 has a metallicity of $[\text{Fe}/\text{H}] \sim -0.2$ (Rutledge, Hesser, & Stetson 1997; Guarnieri et al. 1998; Cohen et al. 1999) and an RGB tip at $M_{I,TRGB} \sim -3.3 \pm 0.2$ (Sagar et al. 1999); 47 Tucanae has $[\text{Fe}/\text{H}] \sim -0.7$ (Carretta & Gratton 1997) and $M_{I,TRGB} \sim -4.05 \pm 0.10$. [The 47 Tuc measurement is based on the fiducial of Da Costa & Armandroff 1990, with an uncertainty derived solely from the range of distance moduli quoted by Hesser et al. (1987); Da Costa & Armandroff (1990); Gratton et al. (1997) and Kaluzny et al. (1998).] The results from both methods imply that, if Virgo’s intracluster stars are at the same distance as VCC 1104, then most of the stars must have metallicities between $-0.8 \lesssim [\text{Fe}/\text{H}] \lesssim -0.2$.

Alternatively, it is possible that the populations of VCC 1104 and Virgo’s intracluster stars are similar ($[\text{Fe}/\text{H}] \sim -1$),

³ Note that although our Virgo A field is only $\sim 34'$ from M86, this galaxy probably does not contribute much to our star counts. M86 is ~ 0.2 mag more distant than M87 (Jacoby, Ciardullo, & Ford 1990; Tonry et al. 2001), thus its contribution to our counts should be minimal. Moreover, the extrapolation of the galaxy’s luminosity profile (Caon, Capaccioli, & Rampazzo 1990) produces a surface brightness that is substantially smaller than what is derived seen.

but that the dwarf galaxy is foreground to the bulk of the cluster. If this is the case, the (luminosity-weighted) distance modulus of the intracluster stars would be $(m - M)_I = 31.4^{+0.4}_{-0.2}$, and VCC 1104 would lie in the foreground by ~ 3.5 Mpc. This seems highly unlikely. Binggeli, Tammann, & Sandage (1987) have shown that the dE,N galaxies of Virgo are strongly concentrated around the denser regions of the cluster, and are thus good tracers of the Virgo core regions. In this respect, VCC 1104 is not exceptional: it is projected only $43'$ from M87 (and $9'$ from our field). For this reason alone, we would not expect VCC 1104 to be a foreground object. In addition, the implied distance of VCC 1104 (15.4 ± 0.9 Mpc; Harris et al. 1998) is in excellent agreement with almost all recent distance estimates to the Virgo Cluster core (Ciardullo et al. 1998; Ferrarese et al. 2000; Tonry et al. 2001). If VCC 1104 were moved significantly into the foreground, then a revision would be required in the Cepheid, surface brightness fluctuation, and planetary nebula distance scales. A more likely explanation is that VCC 1104 is, indeed, located near the center of Virgo, and that many of the intracluster stars of Virgo have metallicities between one-fifth and three-fifths solar.

5.0.3. The AGB Population

Just as the RGB stars of Virgo can be used to place limits on the IC stars' metallicity, the AGB component of the system can be used to constrain the population's age. For example, the fits listed in Table 3 exclude AGB populations that extend more than a magnitude above the tip of the red giant branch, *i.e.*, $\Delta I_{AGB} = 0.8^{+0.2}_{-0.2}$. According to the Girardi et al. (2000) models, this measurement demands that the dominant intracluster population be older than about 2 Gyrs, regardless of metallicity. If the intracluster stars of Virgo have their origin in star-forming galaxies, then their ejection into the intracluster medium must have taken place some time ago. Of course, this does not rule out the possibility that the stars were recently removed from early-type galaxies (e.g., Weil, Bland-Hawthorn, & Malin 1997; Korchagin, Tsuchiya, & Miyama 2001).

Unfortunately, our data do not allow us to place an upper limit on the age of the intracluster stars. Although the mean metallicity of Virgo's intracluster stars is probably $[\text{Fe}/\text{H}] \sim -0.5$, it is entirely possible that some of Virgo's intracluster stars are more metal-poor than this. This would result in a population of RGB stars with magnitudes ~ 0.4 mag brighter than the apparent RGB tip and contaminate our AGB measurement.

A more important source of confusion comes from our assumption about the two-dimensional nature of the cluster. The analysis above assumed that all the intracluster stars in the Virgo A and FTV fields are at the same distance. This is probably not the case. Arguments based on the surface brightness fluctuations of elliptical galaxies (West & Blakeslee 2000), the Tully-Fisher relation of spiral galaxies (Fukugita, Okamura, & Yasuda 1993) and the luminosity function of intracluster planetary nebulae (Ciardullo et al. 1998; Feldmeier et al. 1998) all suggest that the Virgo Cluster is elongated along our line-of-sight. If this is true, and a small population of foreground stars do exist, some of our putative AGB stars must be foreground RGB objects. In fact, a careful inspection of Figure 6 suggests that a very small population of objects with $I \sim 25.8$ (about 0.6 mag brighter than our observed AGB tip) may be present in the data. If so, then this feature could be due to a population of foreground AGB stars. (The alternative explanation, a population of young AGB stars associated with the primary RGB component, is unlikely given the small number of stars observed.) Because of the low statistical significance of the feature, we have not included it in any of our models. Nevertheless, it is suggestive that a small population of foreground stars may be present in our fields.

In our two-dimensional model of Virgo, intracluster stars with $I \sim 26.5$ are objects near the tip of the AGB. If this is incorrect and these stars are actually red giants, then it would imply the existence of a population that is 3 to 5 Mpc in front of the cluster center. Although this number seems large, it is not totally inconsistent with the cluster's projected diameter of 2 to 3 Mpc.⁴ Moreover, if the stars at the apparent tip of the AGB are actually foreground red giants, then the actual AGB tip might be significantly fainter than estimated ($\Delta I_{AGB} \rightarrow 0$). This would imply a significantly older stellar population. A color-magnitude diagram from the next generation of space-based instruments would greatly assist in clearing up the uncertainties in both the age and metallicity of the IC population.

5.1. Comparison with Planetary Nebula Surveys

The data of the Virgo A and FTV fields suggest that $\sim 10\%$ to $\sim 20\%$ of the Virgo Cluster's *total* light comes from its intracluster population. This is slightly smaller than the values of 20% to 40% that have been found in the IPN searches published to date (Theuns & Warren 1997; Méndez et al. 1997; Feldmeier et al. 1998). One reason for this is that the early IPN counts underestimated the presence of redshifted $[\text{O II}] \lambda 3727$ and $\text{Ly}\alpha$ galaxies in the sample. When this component is (statistically) removed, the IPN numbers drop by $\sim 20\%$ (Ciardullo et al. 2002). A second reason for the discrepancy is that α , the ratio of bright planetary nebulae to parent population luminosity, is uncertain by more than a factor of ~ 5 (Ciardullo 1995). Without some estimate of α , IPN-based measurements of intracluster stars carry a substantial uncertainty. Because the Virgo A and FTV fields have both been included in the recent $[\text{O III}] \lambda 5007$ IPN survey of Feldmeier (2000), it is possible to use our star counts to estimate α in the intracluster environment.

To do this, we must first translate our measurement of intracluster *I*-band surface brightness into an estimate of bolometric luminosity surface density. This requires adopting reasonable values for the population's distance modulus ($(m - M)_o = 31.0$), $V - I$ color (~ 1.2 ; Tonry et al. 2001), and bolometric correction (~ -0.8 ; Jacoby, Ciardullo, & Ford 1990). Using these values, we obtain a bolometric-luminosity surface density for the population of $\sigma_{L,bol} = 1200^{+700}_{-300} L_\odot \text{ arcsec}^{-2}$ for our Virgo A field. (This value is 20% larger than that derived by averaging both fields.)

⁴ Note that this does not contradict our earlier assertion about VCC 1104 – as stated above, dE,N galaxies preferentially lie near the cluster core.

Next, we need an estimate for the number of bright IPN in our field. Feldmeier et al. (1998) (see also Feldmeier 2000) originally found 69 IPN candidates in a 244 arcmin^2 region surrounding our Virgo A field, and 7 candidate IPN in a 200 arcmin^2 region around the FTV field. Unfortunately, these counts are suspect: clouds and variable seeing contaminated the Virgo A IPN list with background galaxies (Kudritzki et al. 2000; Ciardullo et al. 2002) and false detections (see Kudritzki et al. 2000), and the IPN observations of the FTV field are not very deep. Consequently, instead of using the data of Feldmeier (2000), our IPN number counts from a newer IPN survey of Virgo A (for more details, see Feldmeier et al. 2002). In a 1098 arcmin^2 region, Feldmeier et al. (2002) found 32 IPN candidates down to a limiting magnitude of $m_{5007} = 26.8$. If we take this density, statistically subtract background contaminants (Ciardullo et al. 2002), assume a standard form of the planetary nebula luminosity function (Ciardullo et al. 1989), and normalize the IPN density to that of the underlying intracluster light, then we obtain a value for the bolometric luminosity-specific PN number density of $\alpha_{2.5} = 23_{-12}^{+10} \times 10^{-9} \text{ PN } L_{\odot}^{-1}$. The uncertainty comes from the Poissonian errors on the IPN counts, our estimate of the bolometric luminosity surface density, and an estimated 0.1 magnitude error in the IPN completeness magnitude.

Although the uncertainty in $\alpha_{2.5}$ is still rather large, it is good enough to place a constraint on the stellar population of Virgo's intracluster space. Ciardullo (1995) has noted a relation between $\alpha_{2.5}$ and the absolute luminosity (M_B) of the PN's parent galaxy. Most luminous E/S0 galaxies (including several in the Virgo Cluster; Jacoby, Ciardullo, & Ford 1990) have low values of $\alpha_{2.5}$ ($\sim 5 - 10 \times 10^{-9} \text{ PN } L_{\odot}^{-1}$); less luminous, bluer systems have values of $\alpha_{2.5}$ that are high (up to $\sim 50 \times 10^{-9} \text{ PN } L_{\odot}^{-1}$). Although the cause of this behavior is not fully understood, it is apparent that old, metal-rich systems are less efficient at making [O III]-bright planetaries than are intermediate-age, intermediate-metallicity populations.

Our results show that $\alpha_{2.5}$ in Virgo's intracluster population is a factor of two larger than that found in massive early-type galaxies. It is also a factor of ~ 2 larger than the value of $\alpha_{2.5}$ derived for Galactic globular clusters (Jacoby et al. 1997). The number is, however, similar to that commonly seen in sub- L^* systems (*i.e.*, $M_B > -20.5$). This suggests a possible origin for the stars. In addition, the relatively high value of α also brings the IPN-based intracluster light measurements more into line with what we derive from the IC RGB stars (Feldmeier et al. 1998).

Of course, the above calculations assume that the RGB surface densities are directly comparable to the IPN surface densities. If there is any spatial structure in the intracluster light, then the density of stars in our small *HST* field may not be representative of that sampled by the wider-field IPN measurements. In fact, there is some evidence (Feldmeier 2000) to suggest that Virgo's intracluster light is non-randomly distributed. However, at the present time, the data are too sparse to draw any useful conclusion. More ground-based and space-based data are required to address this issue.

5.2. Origin of the IC starlight

Most models for the origin of intracluster light involve the removal of stars and globular clusters from cluster galaxies via tidal encounters, either with the overall cluster potential (Merritt 1984; Dubinski 1999) or with other cluster galaxies during close encounters (e.g., Miller 1983; Malumuth & Richstone 1984; Moore et al. 1996, 1998, see Moore, Quilis, & Bower 2000 for a review). In the models, streams of material are liberated from low-mass (sub- L^*) or low-surface brightness galaxies during each tidal encounter, decreasing the population of such objects dramatically. Each tidal feature is only visible for a time, but, over a Hubble-time, the process can produce a sizeable population of intracluster stars.

One can argue that the most-likely candidates for tidal disruption are small, loosely-bound dwarf galaxies. Indeed, the fan-shaped halo surrounding M87 is probably the remains of such an object (Weil, Bland-Hawthorn, & Malin 1997), and numerical simulations of CDM universes predict that large numbers of dwarf galaxies should have been formed in clusters (e.g., White & Frenk 1991; Kauffmann, White, & Guiderdoni 1993; Cole et al. 1994; Klypin et al. 1999). Moreover, Côté, Marzke, & West (1998) have suggested that the *metal-poor* globular clusters associated with giant ellipticals (such as M87) can be explained via the merging or stripping of large numbers of low-luminosity dwarfs. It is thus tempting to conclude that most (or all) intracluster stars have their origin inside dwarf galaxies. However, normal spiral and elliptical galaxies are also susceptible to tidal forces. In fact, the large, low surface-brightness plumes of material seen in Coma and Centaurus almost certainly come from normal-sized galaxies (Trentham & Mobasher 1998; Gregg & West 1998; Calcáneo-Roldán et al. 2000). Hence the question: where do the intracluster stars come from?

Let us first hypothesize that the intracluster stars of Virgo are, indeed, the remains of tidally stripped dwarf galaxies. The total bolometric luminosity of all galaxies within 2° of M87 is $\sim 10^{12} L_{\odot}$ (Binggeli, Sandage, & Tammann 1985); in this same region, the total luminosity of all dwarf and Im galaxies is $\sim 8 \times 10^{10} L_{\odot}$. Thus, dwarf galaxies account for $\sim 8\%$ of the total galactic light. If we now assume that the radial distribution of intracluster light is similar to that of the galaxies, then the star counts in our two *HST* fields imply that the total amount of intracluster light in the 2° core of Virgo is $\sim 1.7 \times 10^{11} L_{\odot}$. In other words, if the intracluster stars come primarily from disrupted dwarfs, then the original number of such galaxies must have been roughly *three times* that observed today. This is possible, though difficult to prove. Moreover, in their consideration of the cD galaxy NGC 1399, Hilker, Infante, & Richtler (1999) concluded that, though the assimilation of dwarfs could explain the luminosity of the galaxy's envelope, it could not explain the galaxy's large number of globular clusters. Thus, despite the susceptibility of dwarf galaxies to tidal disruption, there is no strong evidence to support the idea that *most* of Virgo's intracluster stars come from these objects.

On the other hand, there is evidence to suggest that most of Virgo's intracluster stars come from non-dwarf galaxies. The mean metallicity of the Virgo RGB population lies in the range $-0.8 \lesssim [\text{Fe}/\text{H}] \lesssim -0.2$; the luminosity-metallicity relation of Côté et al. (2000) demonstrates that this is substantially greater than that of most dwarfs. It is, however,

compatible with models of galaxy harassment (Moore et al. 1998, 1999), in which intracluster light is gradually built up by the removal of stars from sub- L^* disks and intermediate-luminosity E/S0 systems. The high value of α derived above for the intracluster population is also in broad agreement with these models.

It is important to note that this conclusion is by no means definitive. We cannot rule out the existence of a substantial population of metal-poor stars, so dwarf galaxies may still be an important contributor to Virgo's intracluster light. Furthermore, our results are still consistent with CDM models of cluster formation. Although metal-poor proto-galactic fragments do not appear to dominate the intracluster light, most of these objects may have long ago been assimilated into galaxies (e.g., Searle & Zinn 1978; Harris & Pudritz 1994). If so, then only the small, relatively isolated systems would have lived long enough to form stars and eventually be disrupted by the cluster's tidal field. These stars could easily be dominated by metal-rich objects liberated by galaxy harassment.

6. CONCLUSIONS

We have analyzed deep F814W *HST* images of a single Virgo cluster field located 41' NW of M87, near the cluster center. Photometry of the unresolved objects in this field (combined with data from another Virgo cluster field observed by Ferguson, Tanvir, & von Hippel 1998) shows an excess of objects (with respect to the background HDF-N and HDF-S fields) with $I \gtrsim 27$, which we attribute to intracluster RGB stars in the Virgo cluster. We derive an average surface brightness of $\mu_I = 27.9^{+0.3}_{-0.5}$ mag arcsec $^{-2}$ for both fields; if our data are representative of the cluster's IC light in general, then IC stars comprise $15^{+7}_{-5}\%$ of Virgo's total light. This result is similar to that obtained from observations of IC planetary nebulae for values of $\alpha_{2.5} = 23^{+10}_{-12} \times 10^{-9}$ PN L_{\odot}^{-1} .

We have modelled the resulting luminosity function with a single-component RGB+AGB population, and derived the location of both the RGB tip ($I_{TRGB} = 27.31^{+0.27}_{-0.17}$) and the bright extent of an AGB ($\Delta I = 0.8^{+0.2}_{-0.2}$). We note, however, that the latter is probably contaminated by foreground RGB stars. We find that the RGB tip is significantly fainter than that observed in a Virgo cluster dE,N galaxy (Harris et al. 1998), and suggest that this difference is due to a higher metal abundance for the intracluster stars ($-0.8 \lesssim [\text{Fe}/\text{H}] \lesssim -0.2$). Our measurement of the intracluster AGB population indicates that the stars are old ($t > 2$ Gyr), but due to the possible existence of a foreground RGB component, we cannot place a firm limit on the population age. From our observations, it seems most likely that the bulk of Virgo's intracluster stars were once stripped from lower-mass spiral and elliptical galaxies, but we cannot rule out the possibility that a significant metal-poor population (such as that expected from tidally stripped *dwarf* galaxies) exists. It is clear that measurements of the metallicity distribution of IC stars will be the key to understanding their origins.

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TABLE 1
LIMITING MAGNITUDES

Field	I_{lim}	β
Virgo A	27.69	1.55
FTV	27.63	1.60
HDF-N	27.61	1.62
HDF-S	27.61	1.53

TABLE 2
LUMINOSITY FUNCTIONS

I	Virgo A ^a		FTV ^a	
	N_c	σ	N_c	σ
25.5	-1.2	1.5	1.8	2.3
25.6	3.3	2.4	3.3	2.4
25.7	3.5	2.1	4.5	2.3
25.8	-1.2	1.5	4.8	2.9
25.9	2.9	2.1	8.9	3.3
26.0	1.1	2.7	0.1	2.5
26.1	0.1	2.5	3.1	3.0
26.2	0.5	3.0	1.5	3.2
26.3	2.6	3.1	3.6	3.2
26.4	10.6	4.2	5.6	3.5
26.5	10.5	4.4	3.5	3.5
26.6	5.5	3.8	10.5	4.4
26.7	14.2	5.1	14.2	5.1
26.8	23.8	6.5	17.8	6.1
26.9	14.4	6.3	24.4	7.1
27.0	17.1	6.9	24.1	7.4
27.1	43.6	8.6	29.6	7.7
27.2	51.8	9.8	31.8	8.7
27.3	81.2	11.2	47.2	9.6
27.4	106.1	12.4	68.1	10.7
27.5	130.8	13.2	78.8	11.1
27.6	129.8	13.2	71.8	10.8

^abackground-corrected

TABLE 3
LUMINOSITY FUNCTIONS - BEST FIT MODELS

Field	I_{TRGB}	ΔI_{AGB}	$\mu_I(RGB + AGB)^1$	χ^2_ν
Virgo A	$27.31^{+0.39}_{-0.19}$	$0.7^{+0.3}_{-0.3}$	$30.08^{+0.10}_{-0.18}$	1.14
FTV	$27.51^{+0.34}_{-0.72}$	$0.9^{+0.2}_{-0.3}$	$30.42^{+0.26}_{-0.09}$	0.48
Combined	$27.31^{+0.27}_{-0.17}$	$0.8^{+0.2}_{-0.2}$	$30.28^{+0.11}_{-0.08}$	0.89

¹ I -band surface brightness of scaled LF model for RGB and AGB stars brighter than $I = 28.1$

TABLE 4
MISSING LIGHT CORRECTIONS - I FILTER

ΔI_{RGB}^a	F^b	$\Delta\mu_{ML}^c$
0.3	0.047 ± 0.006	-3.33 ± 0.14
0.4	0.061 ± 0.006	-3.03 ± 0.11
0.5	0.074 ± 0.007	-2.82 ± 0.11
0.6	0.088 ± 0.008	-2.64 ± 0.10
0.7	0.100 ± 0.008	-2.50 ± 0.09
0.8	0.113 ± 0.009	-2.37 ± 0.09
0.9	0.124 ± 0.010	-2.26 ± 0.08
1.0	0.136 ± 0.010	-2.17 ± 0.08

$$^a \Delta I_{RGB} = I_{cut} - I_{TRGB} = 28.0 - I_{TRGB}$$

^bmean fraction of total luminosity (with no AGB) within ΔI_{TRGB} , with rms error

^c‘missing light’ correction

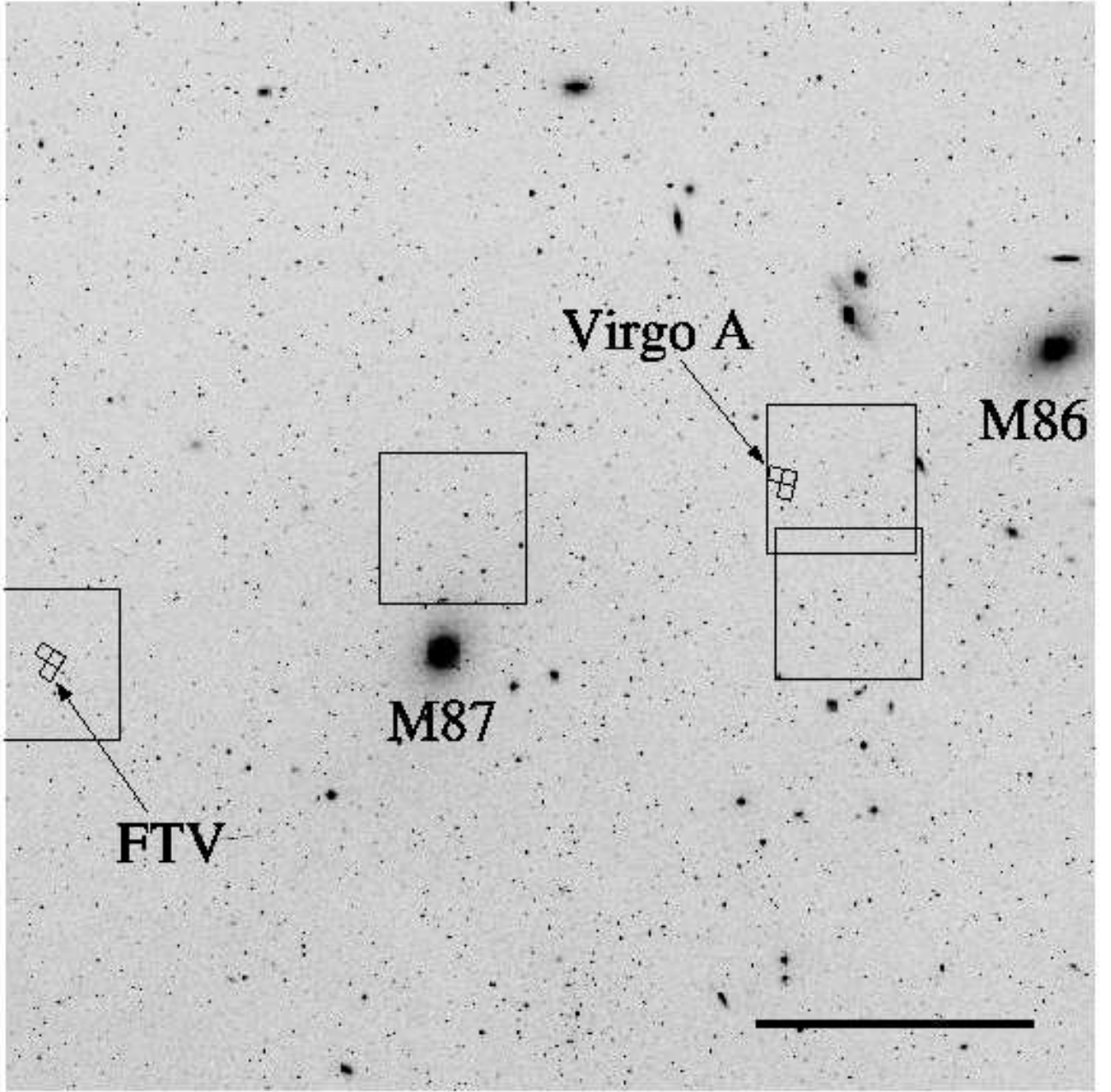


FIG. 1.— A Digitized Sky Survey image of the central region of the Virgo Cluster, with the location of our Subclump A field and the FTV survey field superposed. The image is 2° on a side, with north at the top and east to the left. The solid line at the lower right represents $30''$. Also shown are four Feldmeier (2000) survey fields for intracluster planetary nebulae.

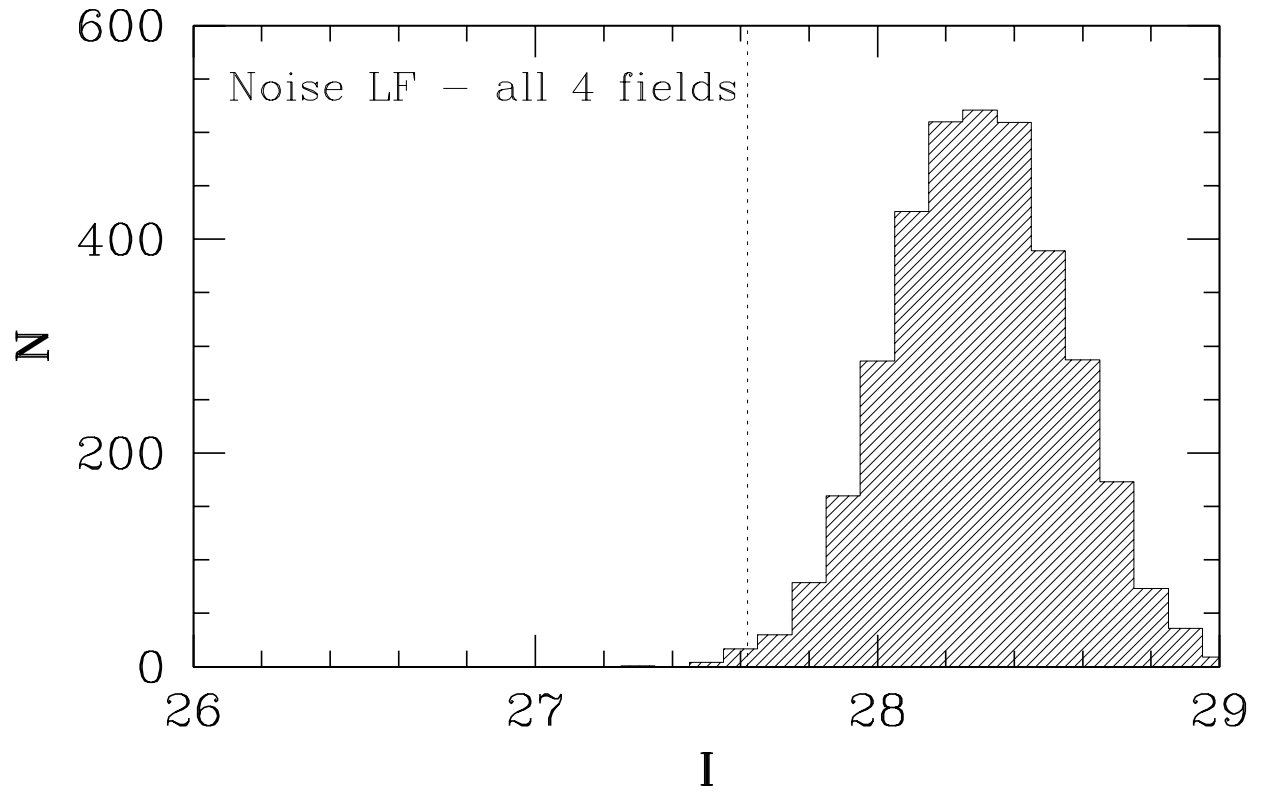


FIG. 2.— The “luminosity function” of noise spikes detected in the inverse images of all four *HST* fields. The data have been binned into 0.1 mag intervals. The dotted line shows the limiting magnitude of our survey. Because of our low detection threshold, the number of false detections is significant for magnitudes $I > 27.6$. At brighter magnitudes, however, contamination of the luminosity by false detections is not important.

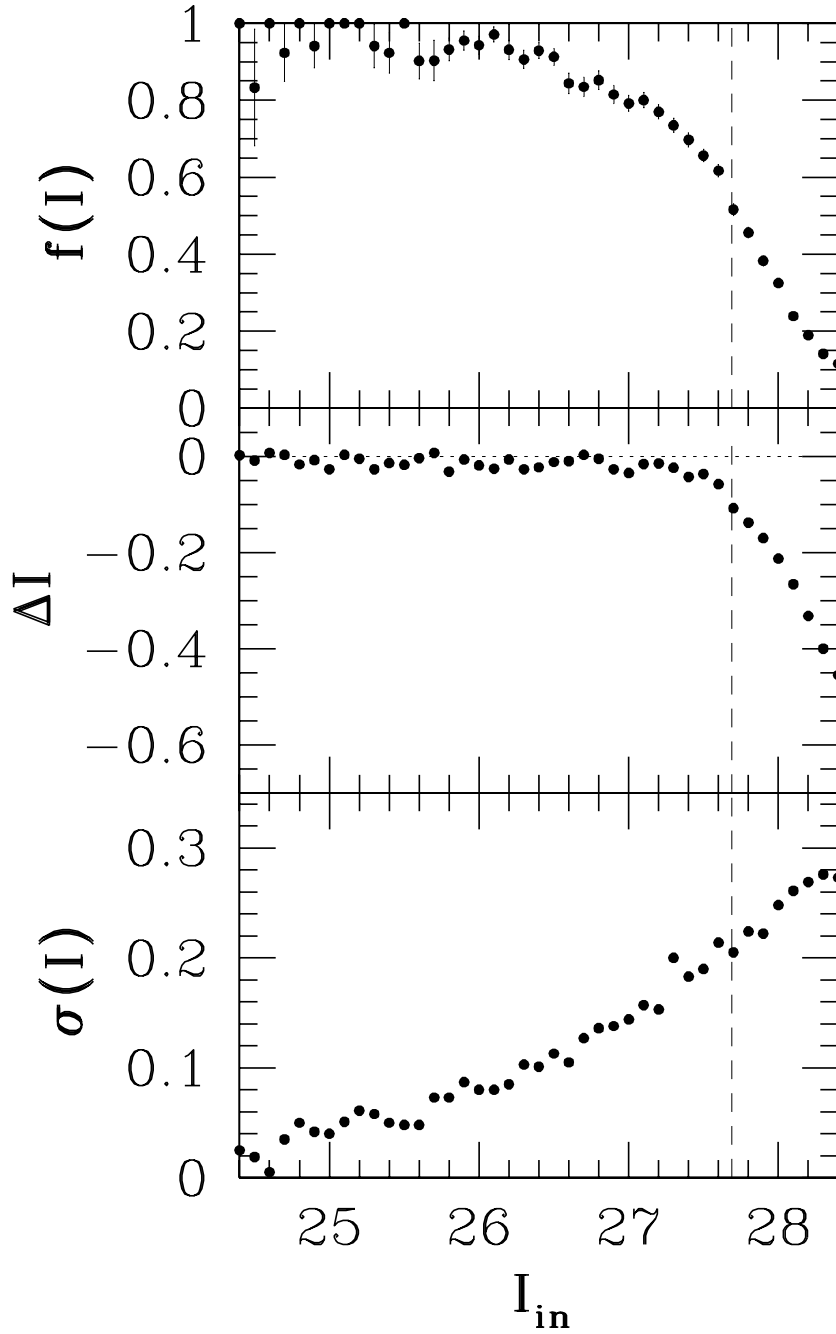


FIG. 3.— Results from artificial star experiments performed on the three WF images in our Virgo A field. The data have been binned into 0.1 mag intervals; I_{in} is the input magnitude of the added stars. The top panel plots $f(I)$, the fraction of artificial stars recovered by our detection algorithm. The center and bottom panels show how the measured magnitudes of the recovered stars relate to the input magnitudes: the center panel plots the difference between the mean measured magnitude and the input magnitude, while the bottom panel gives the dispersion of the distribution. The limiting magnitude of our survey (shown by the dotted line), is defined as the place where the fraction of objects recovered drops to 50%.

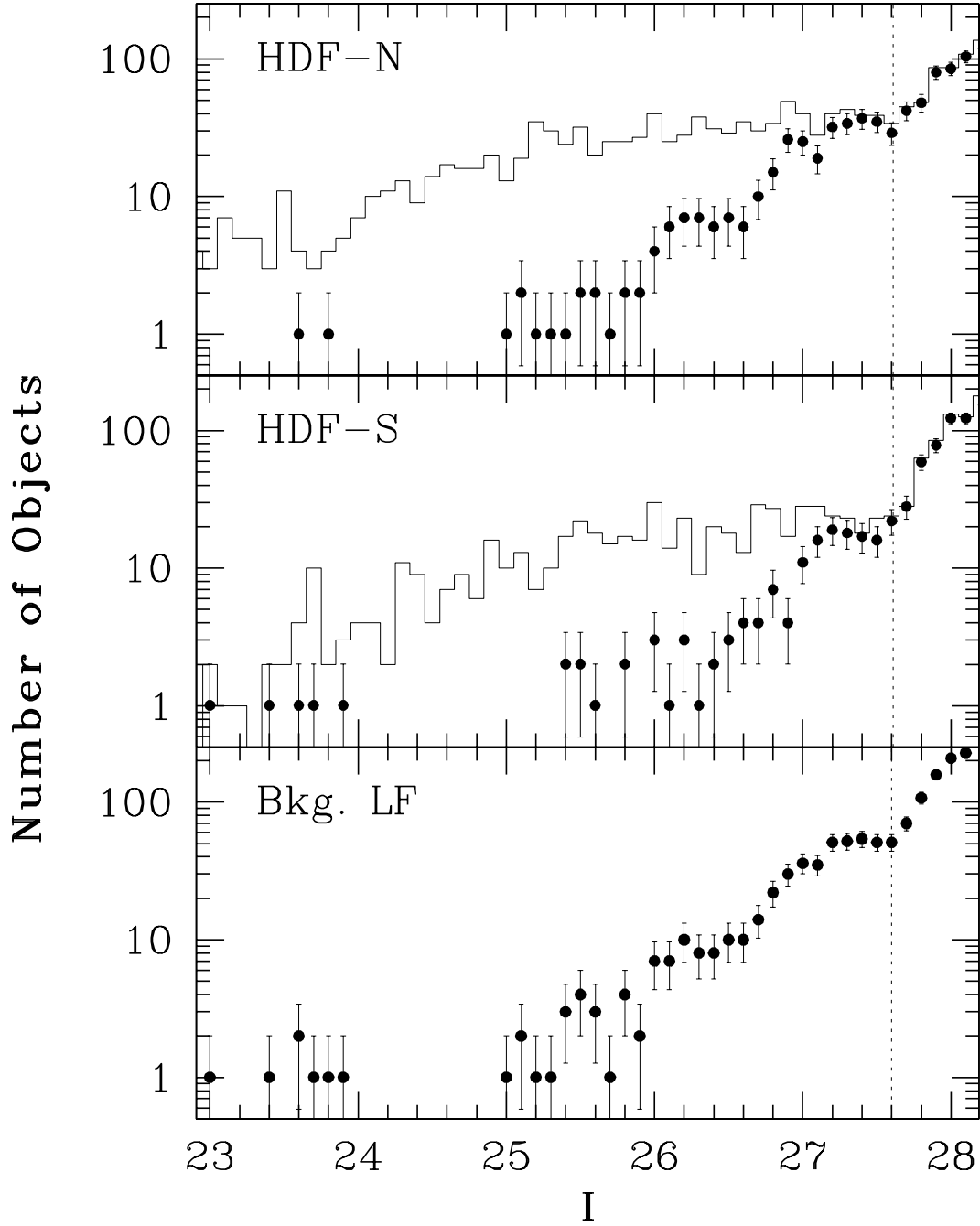


FIG. 4.— The I -band luminosity functions (LFs) of the HDF-N and HDF-S fields, binned into 0.1 mag intervals. The histograms give the total source counts; the solid circles, with their Poissonian error bars, show the LFs after the removal of non-stellar sources. Bins with no counts are not displayed. The dotted line notes I_{lim} , the magnitude where the data is 50% complete. When scaled by their survey areas, the LFs of HDF-N and HDF-S are statistically indistinguishable; their counts can therefore be added to create a total ‘background’ LF. This is displayed in the bottom panel of the figure.

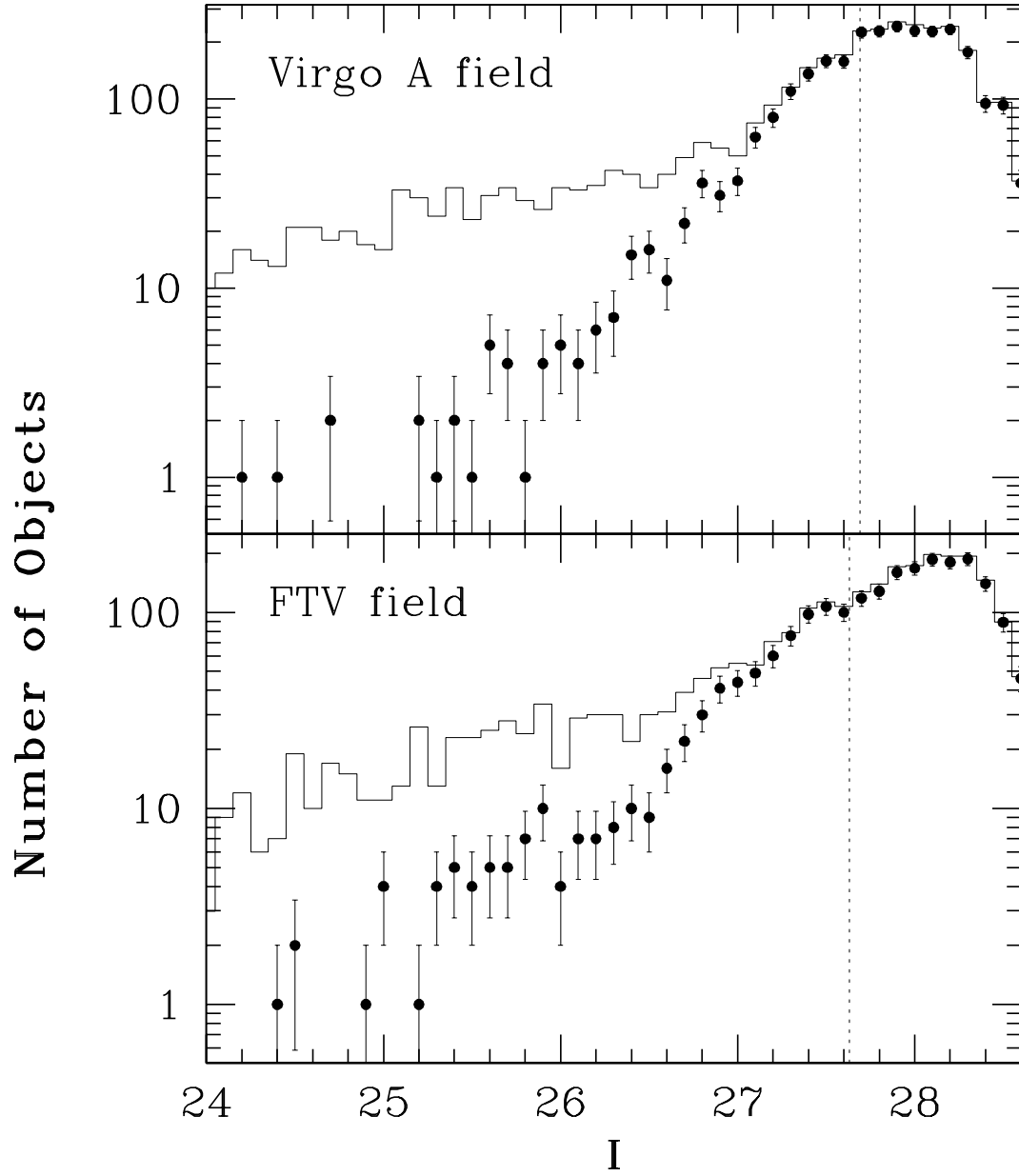


FIG. 5.— The I -band luminosity functions for the Virgo A field and the FTV field, binned into 0.1 mag intervals. The histograms give the total source counts; the solid circles, with their Poissonian error bars, show the LFs after the removal of non-stellar sources. The dotted line notes I_{lim} , the magnitude where the data is 50% complete. As with Figure 4, bins with no source counts are not plotted.

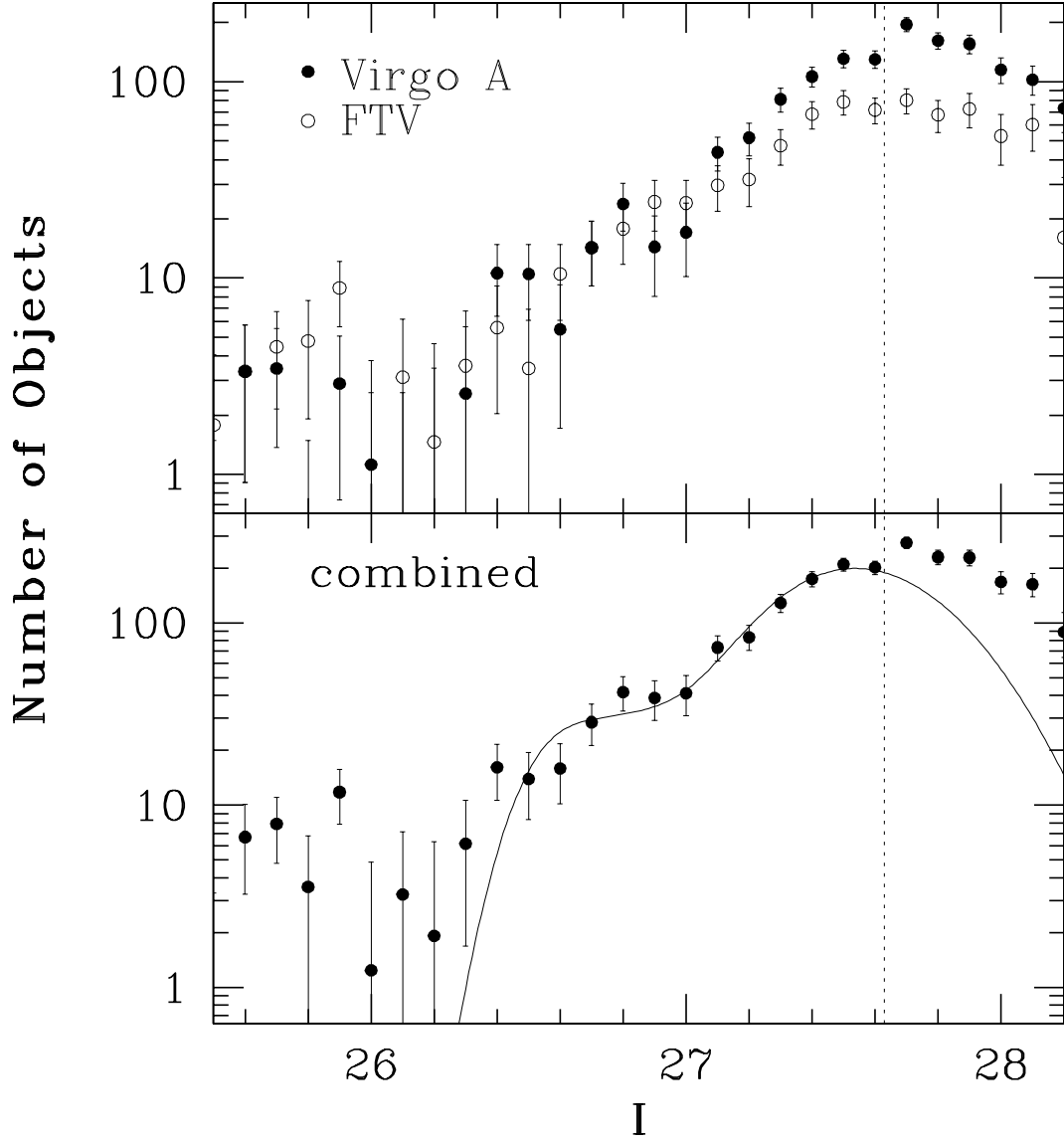


FIG. 6.— The I -band luminosity function (LF) for point sources in our Virgo A field and in the FTV field with the LF of the Hubble Deep Fields removed. The data have been binned into 0.1 mag intervals, and the error bars reflect the Poissonian uncertainties of the Virgo and HDF fields added in quadrature. The data demonstrate that Virgo contains an excess of point sources with $I \gtrsim 26.4$ that this excess becomes dramatically larger at $I \gtrsim 26.8$. The lower panel shows the combination of both background-subtracted LFs, and the corresponding best-fitting RGB+AGB model (see text for details)

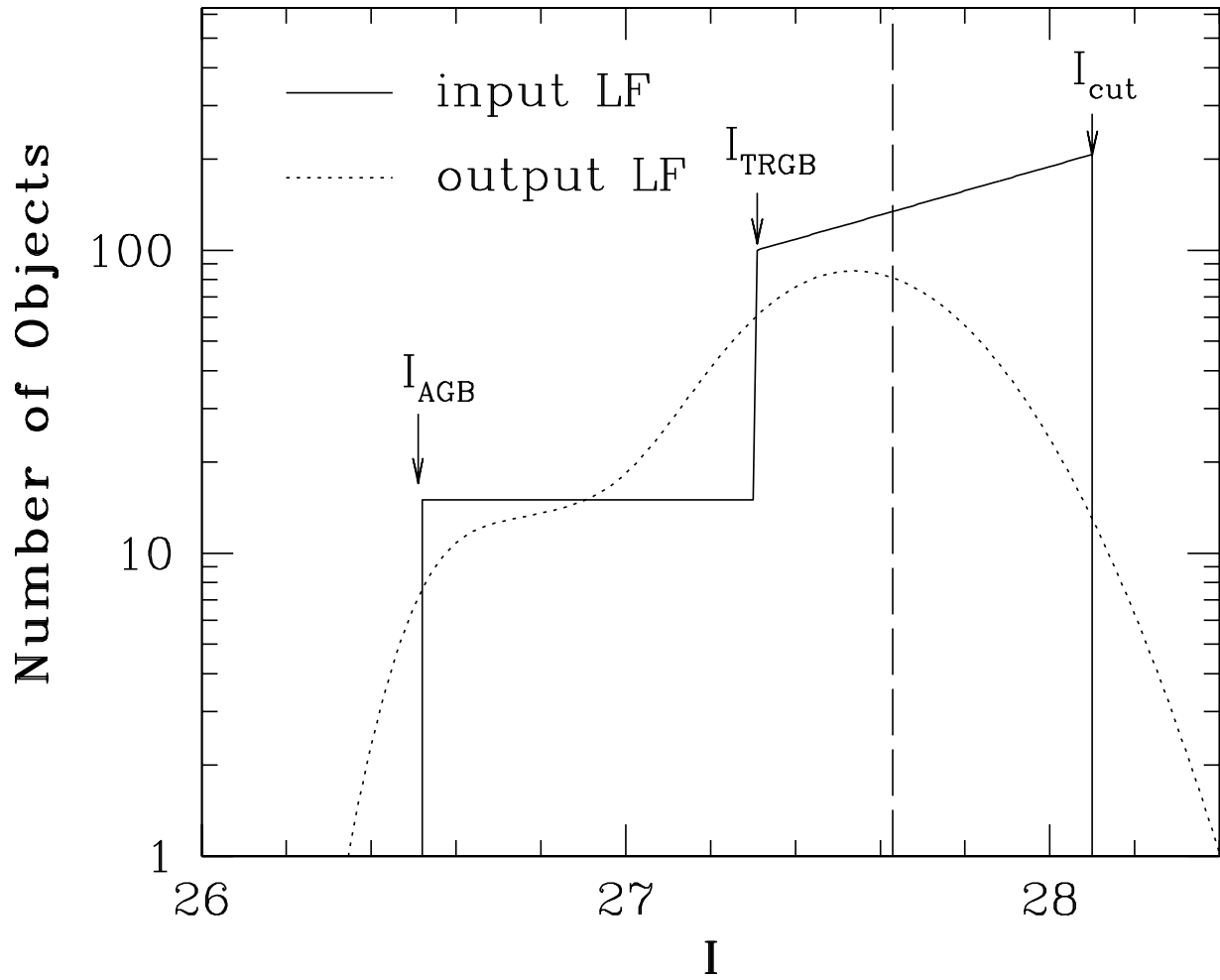


FIG. 7.— A schematic of the intrinsic RGB + AGB luminosity function for Virgo's intracluster stars. The AGB to RGB normalization at the tip of the red giant branch is fixed at 15%; therefore this luminosity function has three free parameters: the tip of the RGB (I_{TRGB}), the magnitude difference between the AGB and RGB tip ($\Delta I_{AGB} = I_{TRGB} - I_{TAGB}$), and the overall normalization of the function. The smooth (dashed) curve is our best-fitting observed LF, which is the intrinsic LF (solid line) convolved with the photometric error function and corrected for incompleteness.

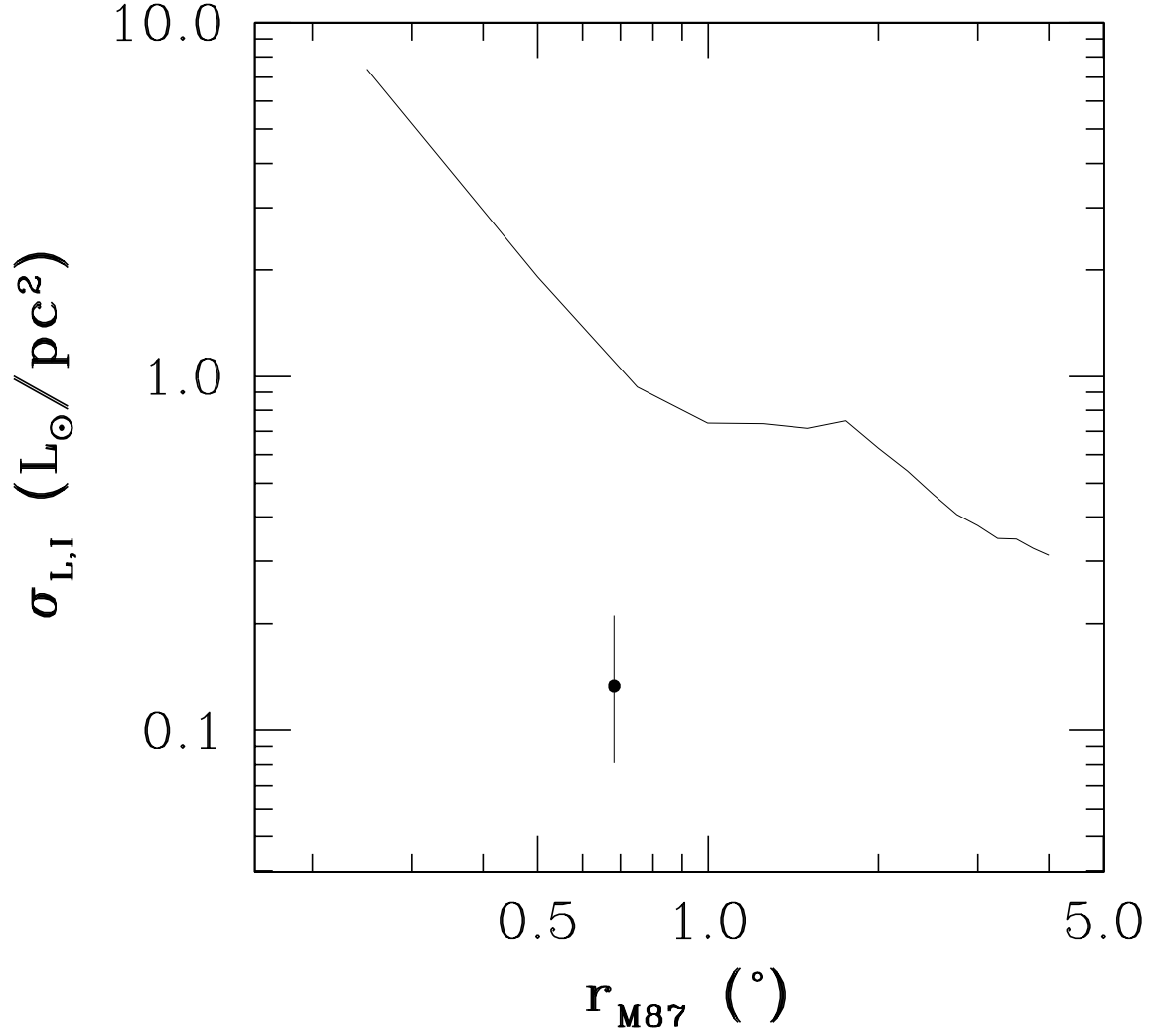


FIG. 8.— The cumulative luminosity surface density $\sigma_{L,I}$ (solid line) for member galaxies in the Virgo cluster, as a function of radial distance from M87. The filled circle denotes the surface brightness of intracuster stars derived from our best-fitting model, and includes the corresponding 1- σ error bars.